

# CREEP IN TIMBER: RESEARCH OVERVIEW AND COMPARISON BETWEEN CODE PROVISIONS

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## KEYWORDS

Long-term behaviour of timber, Creep, Visco-elasticity

## ABSTRACT

The design of timber beams and joists is often governed by serviceability requirements, i.e., meeting deflection limits over the life of the structure. Since timber is a visco-elastic material, it is subjected to creep when permanent loads are applied. The amount of creep depends on several variables, e.g., load-to-grain angle, moisture content of timber and stress level, which therefore strongly affect the design. This paper presents an overview of the creep properties of timber, including conceptual models of the material, constitutive laws, and analytical approaches proposed by current building codes. The purpose is to provide a link between the advances in terms of experimental results and theoretical formulations to common design calculations. Redirections to the most relevant studies are reported for the reader interested in a more comprehensive knowledge of each specific topic. Finally, the long-term deflection of a Radiata Pine LVL beam calculated by four different procedures specifically according to New Zealand Standard 3603, Eurocode 5 (European code), National Design Specifications for Wood Construction (North-American code) and Toratti's model is reported. The aforementioned models seem providing consistent results, however the uncertainty in the deflection estimation appears growing in case of more extreme environmental conditions. These discrepancies are believed dependent on how each procedure takes into account the mechano-sorption effect.

## GENERAL PROPERTIES OF CREEP

Timber, due to its particular molecular architecture, presents strain-stress behaviour dependent on time: if subjected to a constant stress, such as permanent loads, it reacts as a viscoelastic material, increasing its deformation with time. This effect is known as creep (Morlier 2004). The long-term behaviour of timber can be divided into three main phases (Findley and Davis 2013), graphically presented in Figure 1:

1. Primary creep: the deformation rapidly increases before reaching a more stable rate;
2. Secondary creep: the rate of deformation is fairly constant or decreasing;
3. Tertiary creep: the deformation rapidly increases leading to the failure of the material.

Whether or not the tertiary phase occurs depends

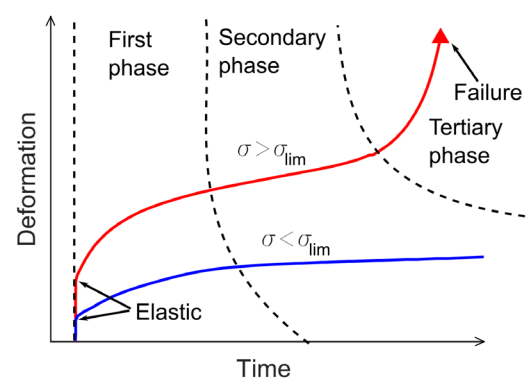


Figure 1: Three phases of creep: 1) primary, 2) secondary and 3) tertiary.

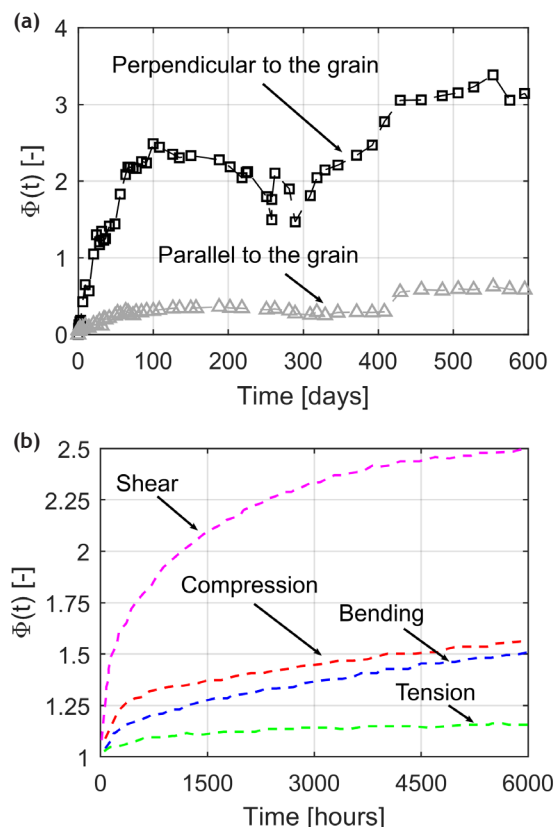
on the stress level  $\sigma$ . To avoid the occurrence of the tertiary phase, and therefore the material failure, Standards, for example Eurocode 5 (2004) (European building code), New Zealand Timber Standard 3603

(1993) and National Design Specifications for Wood Construction (2018) (North-American building code) provide factors to reduce the timber strength to a specific limit  $\sigma_{lim}$  depending on the load duration.

## FACTORS INFLUENCING THE CREEP PROPERTIES

Creep  $\Phi(t)$  is usually expressed as the ratio of the deformation at a specific time after loading  $\varepsilon(t)$  to the elastic deformation  $\varepsilon_{el}$ , i.e.,  $\Phi(t) = \varepsilon(t)/\varepsilon_{el}$ .

The creep behaviour of wood is strongly dependent on the angle between the direction of the force and the grain (Niemz 2004). Specifically, the amount of creep when timber is loaded perpendicular to the grain can reach up to 8 times the amount of creep when timber is loaded parallel to the grain (Morlier 2004). In Figure 2a, recent results obtained by Wanninger et al. (2014) are shown.



**Figure 2:** A) different creep behaviour for wood loaded parallel and perpendicular to the grain (modified from Wanninger et al. (2014)), and B) creep behaviour for different stress actions in beams (modified from Gressel (1984)).

The two creep curves represent the creep observed in glulam ash block specimens loaded perpendicular to the grain, and glulam spruce block specimens loaded parallel to the grain under constant compression stress in uncontrolled environmental conditions. It

can be seen that the creep perpendicular to the grain was 5 times higher than the creep observed parallel to the grain.

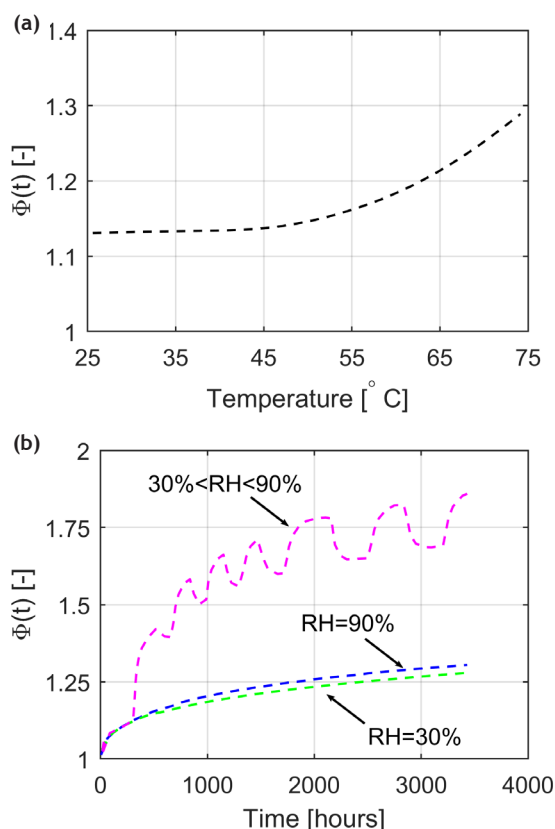
Because of this orthotropic behaviour, the nature of stress can affect the creep trend as found by Gressel (1984). By testing several beam specimens, Gressel (1984) reported that shear leads to the higher value of creep deformation, whereas tension leads to the minimum value (see Figure 2b). This trend is consistent with another study performed by Schniewind and Barrett (1972). While testing Douglas fir beam specimens, the creep in shear perpendicular to the grain was found to be 5 times larger than the the creep when bending parallel to the grain.

The environmental conditions, for example temperature and relative humidity, directly and indirectly affect the creep behaviour of wood. Temperature directly affects the creep coefficient, as reported by Morlier (2004). In Figure 3a, the creep measured by Huet et al. (1981) on spruce specimens tested in bending is reported. The moisture content of the specimens was kept constantly at 12%. The measurements were taken after a week, and the specimens were kept at different environmental temperatures. It can be seen that the higher the temperature, the greater is the creep. However, for temperatures below 35 °C, the creep deformation is only slightly affected.

Environmental temperature and relative humidity also affect the moisture content of wood. Specifically, for a given temperature and relative humidity, wood reaches a moisture content in equilibrium with the environment (Buchanan 1999). If the environmental conditions vary, then the moisture content of the timber varies. This variation of timber moisture content accelerates the creep deformation: the effect is commonly known as mechano-sorptive creep, and it was first noted by Armstrong and Kingston (1960).

Several studies have been performed since the 1960s to investigate the interaction between moisture content and creep, for example, Amrstrong and Kingston (1960), Grossman (1978), Hoffmeyer and Davidson (1989), Hanhijarvi and Hunt (1998), Olsson et al. (2007); however, because of its complexity, the topic is still an object of research.

In Figure 3b, the creep behaviour of three specimens tested by Hanhijarvi (1995) is reported. The specimens were tested in three different environmental



**Figure 3:** A) Creep coefficient dependence on environmental temperature (modified from Huet et al. (1981)), and B) coefficient dependence on relative humidity (modified from Hanhijarvi (1995)).

conditions, represented by 1) constant relative humidity equal to 30% (RH = 30%), 2) constant relative humidity equal to 90% (RH = 90%) and 3) variable relative humidity with cycles between 30% and 90%. It can be seen from Figure 3b, that the variation of relative humidity produces an increase in creep of around 300% with respect to the cases with constant relative humidity.

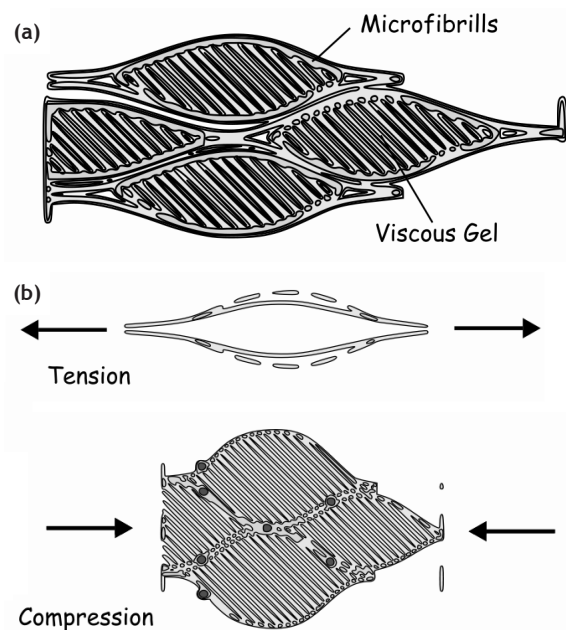
## CONCEPTUAL MODELS

Several conceptual models exist to better visualize and explain the creep behaviour of wood. Moorkamp (2002) and Hanhijarvi (1995) collected the most relevant ones, and a good summary was given by Schanzlin (2010). Below, two principle models proposed by Boyd (1982) and Grossman (1978) are described.

### The Boyd model

According to Boyd (1982), the fibres of timber are composed of microfibrils and a viscous gel embedded between them (see Figure 4a).

The normal creep strain is explained by the yielding of



**Figure 4:** Microfibrils model according Boyd (1982): A) microfibrils structure and B) reaction to external tension or compression forces (images modified from Schanzlin (2010)).

the gel, whereas the mechano-sorptive creep depends on its shrinkage. When shrinking occurs, the resulting gap between the microfibril surfaces introduces an additional deformation associated with mechano-sorptive creep.

Because the microfibrils are directly stretched when subjected to tension forces (see Figure 4b), they are taking a great part of the load. Therefore, a lower level of force is expected to be acting on the gel. In the opposite case, when timber is loaded in compression, the gel takes more load than in the previous case. Since the yielding of the gel is responsible for the creep behaviour, it is clear that the creep in tension is going to be lower than the creep in compression, as experimentally observed (see Section 2).

The force-to-grain angle dependency can be considered as force-to-microfibrils dependency. Loading parallel to the grain means loading mostly the microfibrils, whereas loading perpendicular to the grain means loading the gel directly. Again, because the yielding of the gel is responsible for the creep behaviour, it is clear that the creep perpendicular to the grain would result in higher values.

### The Grossman Model

In Grossman's (1978) opinion, the breaking of the hydrogen bonds between the cellulose chains (Figure 5) is responsible for the creep in wood. Two types of bonds are considered: strong bonds and weak bonds.

The so-called strong hydrogen bonds can be broken by mechanical loads, resulting in a slip between the cellulose chains. This slip on the micro-scale results in the macro-scale deformation called creep. Whenever the moisture content varies, the weak hydrogen bonds break because they are affected by water. This phenomenon introduces an extra contribution to the total slip, which at macro-level is observed as mechano-sorptive creep.

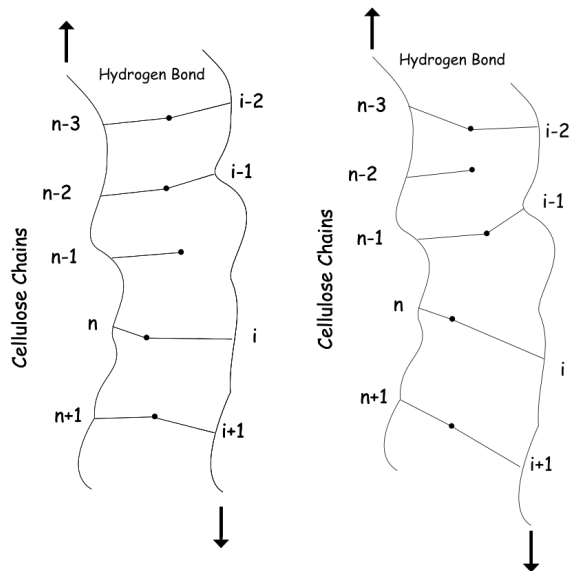


Figure 5: Cellulose chains in the Grossman model (1978) (image modified from Schanzlin (2010)).

The influence of stress level on creep deformation is determined by the number of bonds broken, resulting in larger creep deformations when higher stress is applied. The larger the slip, the lower the probability that the broken parts find partners to re-establish a new bond, resulting in a softer system. At macro-level, the higher the tension, the greater the non-linearity that can therefore be observed in the creep behaviour.

## STANDARDS APPROACH

The Standards approach, dealing with the long-term behaviour of timber, focuses on two main aspects:

1. providing **strength reduction factors** to avoid the occurrence of the tertiary creep phase;
2. providing **creep coefficients** to be multiplied by the elastic deformation, so giving an indication of the total deformation expected at the end of the structural life.

In the following section, the approach of the Eurocode 5 (2004), the New Zealand Standard 3603

(1993) and the National Design Specification for Wood Construction (2018) are presented.

## Eurocode 5

Because timber behaviour is strongly dependent on the moisture content exchanged between the material and the environment, Eurocode 5 (2004), takes into account this information through the concept of "Service Class". The Service Class is defined as the environmental conditions, that is, temperature and relative humidity that the material will be subjected to during the life of the structure. In other words, Service Classes represent the demand in terms of humidity and temperature which will affect the properties of the material during the life of the structure. Eurocode 5 Part 1-1 Section 2.3.1.3 (2004) proposes the following classification:

1. Service Class I is characterized by a moisture content in the material corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year.
2. Service Class II is characterized by a moisture content in the material corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year.
3. Service Class III is characterized by climatic conditions leading to higher moisture contents than in Service Class II

The **load carrying capacity**  $R_d$  of a member is calculated as:

$$R_d = k_{mod} \frac{R_k}{\gamma_M} \quad (1)$$

where  $R_k$  is the characteristic load carrying capacity,  $\gamma_M$  the partial safety factor for the material property and  $k_{mod}$  the reduction factor due to long-term effects.

Based on the Service Class, Eurocode 5 (2004) at Section 3.1.3 proposes different strength reduction factors  $k_{mod}$ , which are reported in Table 1.

It can be seen that the  $k_{mod}$  factors generally decrease when the load duration increases, or when the Service Class is higher. In other words, if the duration of the load is longer or the environmental conditions are more demanding, the allowable stress on timber must be lower to avoid the occurrence of the tertiary creep phase.

If the stress applied is within the strength limits

Table 1: Strength reduction factors  $k_{mod}$  according to Eurocode 5 (2004) (note: values reported only for solid timber, Glue Laminated timber, LVL and plywood)

Material	Standard	Service Class	Load-duration class				
			Permanent	Long-term	Medium-term	Short-term	Instantaneous
Solid Timber	EN 14081-1	1	0.6	0.7	0.8	0.9	1.1
		2	0.6	0.7	0.8	0.9	1.1
		3	0.5	0.55	0.65	0.7	0.9
Glue Laminated Timber	EN 14080	1	0.6	0.7	0.8	0.9	1.1
		2	0.6	0.7	0.8	0.9	1.1
		3	0.5	0.55	0.65	0.7	0.9
LVL	EN 14374 EN 14279	1	0.6	0.7	0.8	0.9	1.1
		2	0.6	0.7	0.8	0.9	1.1
		3	0.5	0.55	0.65	0.7	0.9
Plywood	EN 636-1	1	0.6	0.7	0.8	0.9	1.1
	EN 636-2	2	0.6	0.7	0.8	0.9	1.1
	EN 636-3	3	0.5	0.55	0.65	0.7	0.9

\*Note: for timber that is installed at or near its fibre saturation point, and which is likely to dry out under load, the values of  $k_{def}$  should be increased by 1.

derived by applying the factors in Table 1, creep is considered by the Standard as linear viscoelastic. In this hypothesis, the Standard suggests calculating the long-term deformation as a multiple of the elastic deformation under permanent loads.

Instead of directly multiplying the elastic deformation, Eurocode 5 at section 3.1.4 provides  $k_{def}$  **factors to reduce the elastic modulus of the material  $E$**  into an effective modulus  $E_{eff}$  according to Equation 2:

$$E_{eff} = \frac{E}{1 + k_{def}} \quad (2)$$

In other words, the material is considered more flexible to take into account the extra amount of deformation due to creep. The  $k_{def}$  factors are reported in Table 2. It can be seen that the higher the Service Class, the higher the value of  $k_{def}$ , and therefore the higher the deformation.

### New Zealand Timber Standard NZS: 3603

The approach provided by the New Zealand Standard

Table 2: Long-term amplification factors  $k_{def}$  for deformation of according to Eurocode 5 (2004) (values reported only for solid timber, Glue Laminated timber, LVL and plywood).

Material	Standard	Service Class		
		I	II	III
Solid timber	EN 14081-1	0.6	0.8	2
Glue Laminated Timber	EN 14080	0.6	0.8	2
LVL	EN 14374 EN 14279	0.6	0.8	2
Plywood	EN 636-1	0.8	-	-
	EN 636-2	0.8	1	-
	EN 636-3	0.8	1	2.5

\*Note: for timber that is installed at or near its fibre saturation point, and which is likely to dry out under load, the values of  $k_{def}$  should be increased by 1.

(1993) is similar to the one provided by Eurocode 5 (2004), with the difference that no distinction is made with regard to the moisture content variation. In terms of **strength reduction** due to long-term effects  $R_d$ , the characteristic  $R_k$  should be multiplied by  $k_1$  factors according to Equation 3:

$$R_d = k_1 \cdot R_k \quad (3)$$

The Standard provides  $k_1$  factors at Section 2.7, which are here reported in Table 3. It can be seen that the higher the load duration, the lower the strength. However, no distinction is made for different environmental conditions as proposed by the Eurocode 5 (2004).

Table 3: Strength reduction factor  $k_1$  according to New Zealand Standard 3603 (1993).

Duration of load	Examples	$k_1$
Permanent	Dead and live loads that are essentially permanent such as stores (including water tanks and the like), library stacks, fixed plants, soil pressures.	0.6
Medium	Snow loads, live loads, crowd loadings, concrete formwork, vehicle, pedestrian and cattle loadings.	0.8
Brief	Wind, earthquake, impact, erection and maintenance loadings, pile driving.	1.0

In terms of long-term deformation (i.e. creep), the hypothesis of linear viscoelastic behaviour is also made. Therefore, the long-term deformation  $\epsilon_\infty$  is calculated according to Equation 4:

$$\epsilon_\infty = k_2 \cdot \epsilon_{el} \quad (4)$$

where  $\epsilon_{el}$  is the elastic deformation and  $k_2$  the amplification factor. Values of  $k_2$  are reported in Table



4.

It can be seen from Table 4 that the  $k_2$  factor depends on the duration of the load, the initial moisture content and the nature of the stress. Specifically: 1) the higher the initial moisture content, the higher is the long-term deformation expected; 2) the higher the load duration, the higher the long-term deformation expected; and 3) bending, compression and shear forces produce higher long-term deformation than do tension forces.

#### National Design Specification for Wood Construction

Similar to the Eurocode 5 (2004), the Design Specification for Wood Construction (NDS) (2018) provide a classification regarding the moisture service condition of timber, as well as load duration factors to avoid the tertiary phase of creep. In terms of moisture effect for sawn timber, at section 4.1.4 it is reported:

*The reference design values for lumber specified herein are applicable to lumber that will be used under dry service conditions such as in most covered structures, where the moisture content in use will be a maximum of 19%, regardless of the moisture content at the time of manufacture. For lumber used under conditions where the moisture content of the wood in service will exceed 19% for an extended period of time, the design values shall be multiplied by the wet service factors  $C_M$ .*

Such reference value of moisture is equal to 16% when looking at prefabricated timber element such as joist, glue laminated timber and cross laminated timber glue laminated timber (see section 5.1 4, 7.1.4 and 10.1.4 of NDS (2018)).

The values of  $C_M$  are reported in Table 5 for respectively

Table 4: Long-term amplification factors  $k_2$  for deformation according to New Zealand Standard 3603 (1993).

Duration of load	Moisture content at time of loading	$k_2$	
		For bending, compression and shear	For tension
12 months or more	25% or more	3.0	1.5
12 months or more	18% or less	2.0	1
2 weeks or less	Any	1.0	1

Table 5: Wet service factors  $C_M$  according to the NDS (2018) for compression strength parallel to the grain  $F_c$ , compression perpendicular to the grain  $F_{c\perp}$ , tension  $F_t$ , shear  $F_v$  and elastic modulus  $E$ . (\* For prefabricated I joist, LVL and cross laminated timber  $C_M$  is equal to 1 in dry conditions and appropriate values should be provided by the manufacturer for wet conditions.)

	Reference	$F_b$ *	$F_t$	$F_v$	$F_{c\perp}$	$F_c$ *	$E$
Sawn timber	NDS Section 4.1.4	0.85	1.0	0.97	0.67	0.8	0.9
Glue Laminated Timber	NDS Section 5.1.4	0.8	0.8	0.875	0.53	0.73	0.833

sawn timber and glue laminated timber. For prefabricated joist, LVL and cross laminated timber, the values should be provided by the manufacturer. It can be seen that the moisture content differently affects the properties of timber with respect to the nature of the stress, as well as the type of timber product. Table 5 shows the strength perpendicular to the grain suffers the highest penalization, while tension and shear strength are little affected.

Similar to the Eurocode 5 (2004), the strength of timber is affected by a load duration factor. The values of such coefficient, indicated with  $C_d$ , are reported in Table 6. It can be seen that the higher the duration of the load, the lower the  $C_d$  factor.

Since the tertiary creep should be prevented by the use of  $C_M$  and  $C_d$  coefficients, the NDS (2018) allow to calculate the creep deformation within the visco-elastic theory. The **long term deflection**  $\Delta_T$  can be obtained by using Equation 5:

$$\Delta_T = K_{cr}\Delta_{LT} + \Delta_{ST} \quad (5)$$

where  $\Delta_{LT}$  the deflection due to permanent loads,  $\Delta_{ST}$  the deflection due to occupancy-live loads, and  $K_{cr}$  the creep coefficient. The values of  $K_{cr}$  are reported in Table 7 for different products.

Table 6: Load duration factors  $C_D$  according to the NDS (2018).

Load duration	$C_D^{(1)}$	Typical design loads
Permanent	0.9	Dead load
Two years	1.0	Occupancy live load
Two months	1.15	Snow load
Seven days	1.25	Construction load
Ten minutes	1.6	Wind/earthquake
Impact	2.0	Impact load

(1) Load duration factors shall not apply to reference modulus of elasticity,  $E$ , reference modulus of elasticity for beam and column stability,  $E_{min}$ , nor to reference compression strength perpendicular to grain design value,  $F_{c\perp}$ , based on deformation limit.

Table 7: Values of  $K_{cr}$  provided by the NDS (2018).

Product	Dry conditions	Wet conditions
Seasoned lumber	1.5	2
Glue Laminated Timber	1.5	2
Prefabricated wood I-joists	1.5	*
Cross Laminated Timber	2	*

Note \* values should be provided by the manufacturer.

## RHEOLOGICAL MODELS FOR TIMBER: NUMERICAL MODELLING

Modelling <sup>1</sup> the creep behaviour of timber is a complex and rather difficult task to perform. Even now, it is still an open research topic with many researchers proposing innovative numerical techniques and rheological models (Dubois et al. 2005; Frandsen et al. 2007; Vidal-Sallé and Chassagne 2007; Fortino et al. 2009; Hassani et al. 2015).

Among the several complexities that a complete model should be able to capture (Holzer et al. 2007), two main purposes can be identified : 1) the simulation of the variation of the timber's moisture content with respect to the variation of environmental temperature and relative humidity, and 2) the definition of the stress-strain relationship, that is, a timber constitutive law.

### Moisture transportation within wood

The mechanics of moisture transportation in wood is still an object of research. The most advanced models rely on non-Fickian approaches (Wadsö 1994; Krabbenhoft and Damkilde 2004) or multi-Fickian (Frandsen et al. 2007). Their formulation is rather complex and requires the definition of several material parameters.

<sup>1</sup>This section provides a literature review regarding the current numerical models adopted for simulating the long-term behaviour of timber. The content is presented in its theoretical formulation, and it is directed to the reader interested in developing more advanced simulations. For design purposes, the reader is redirected to the section "Creep deformation of a LVL beam: comparison between building codes."

Fickian models, although representing a simplification of the problem, are probably the most used (Fortino et al. 2009; Khorsandnia et al. 2015; Hassani et al. 2015). They rely on two main assumptions (Krabbenhoft and Damkilde 2004): 1) the moisture flux is described by a Fickian-type gradient law, and 2) the water in the boundary cells is at all times in equilibrium with the surrounding mixture of vapour and air.

According to the Fickian model, the spatial distribution of the moisture content  $u(x, y, z, t)$  over time  $t$  can be expressed by Equation 6 (Figure 6):

$$\frac{\partial u}{\partial t} = D_x \frac{\partial^2 u}{\partial x^2} + D_y \frac{\partial^2 u}{\partial y^2} + D_z \frac{\partial^2 u}{\partial z^2} \quad (6)$$

where  $D_x$ ,  $D_y$  and  $D_z$  represent the diffusivity coefficients with respect to the  $x$ ,  $y$  and  $z$  axes, respectively.

It has to be noted that, generally speaking, the diffusivity along parallel to the grain (direction  $x$  in Figure 6) is in the range of ten times the diffusivity perpendicular to the grain (Fortino et al. 2009). Therefore, the moisture transfer is facilitated when a timber member is left exposed to the air allowing the moisture to enter parallel to the grain. For this reason, it is common practice to protect the ending zones of columns (Figure 7) to prevent humidity going inside. This would not only reduce the amount of creep, but also preserve the durability of the member by avoiding the formation of fungi (Brischke et al. 2013).

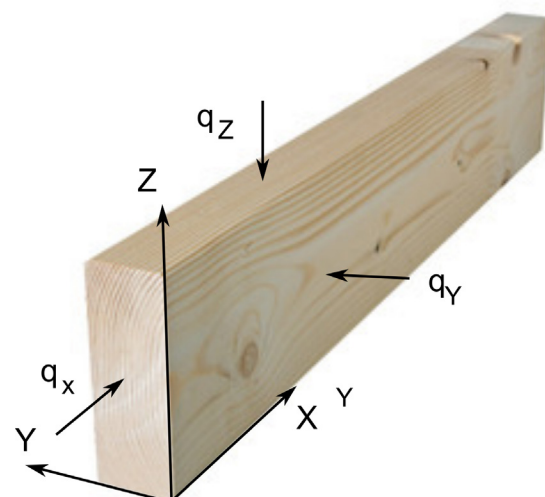


Figure 6: Graphical representation of the humidity fluxes expressed by Equation 6.



Figure 7: Example of column detailing.

A common expression for the diffusion parameter  $D$  (without looking at any specific direction) is represented by equation 7 (Toratti 1992):

$$D(u) = D_0 e^{2.28u} \frac{cm^2}{day} \quad (7)$$

where  $D_0$  a material parameter and  $u$  the moisture content. It is worthy to note that the diffusivity is proportional to the exponential of the moisture content. This fact means that the more timber is absorbing humidity, the more this process is encouraged.

In practical applications Equation 6 is implemented in finite element software and numerically integrated to find the moisture distribution over time within the timber element or structure (e.g. Fortino et al. 2009).

#### Stress-strain relationship

The stress-strain viscoelastic behaviour of wood presents strongly non-linear characteristics. As outlined by Schaffer (1972):

”Wood behaves non-linearly over the whole stress-level range, with linear behaviour being a good approximation at low stresses. Because of this nearly linear response at low level of stress, Boltzmann’s superposition principle applies to stress-strain behaviour for stresses up to 40% of short time behaviour”.

The most recent constitutive laws (Hassani et al. 2015) are able to include non-linearities in the material stress-strain relationship, such as plasticity. Such constitutive laws are rather complex to define and implement, and above all require several material parameters to describe a specific wood product.

If the applied stress is small enough, a valid alternative is represented by linear viscoelastic constitutive laws (Mårtensson 1992; Toratti 1992; Hanhijärvi 1995; Becker 2002). These have the advantage of being easier to implement, and they require fewer material parameters in defining a wood species.

Furthermore, because the problem becomes linear, the solution can be calculated by using Boltzman’s superposition principle, which significantly reduces the computational effort.

Among these linear viscoelastic constitutive laws, Toratti’s model version B is one of the most widely used (Fragiacomo 2005; Fortino et al. 2009; Khorsandnia et al. 2015). According to Toratti (1992) and Svensson and Toratti (2002), the stress-strain moisture-dependent relationship of timber can be written in the following integral form:

$$\begin{aligned} \epsilon(t) = & \underbrace{\int_{t_0}^t J_0(u(\tau)) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau + \int_{t_0}^t \sigma(\tau) \frac{\partial J_0(u(\tau))}{\partial u(\tau)} du(\tau)}_{\text{Elastic strain}} + \underbrace{\int_{t_0}^t J_c(t, \tau) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau}_{\text{Creep strain}} \\ & + \underbrace{\int_{t_0}^t \left(1 - e^{-c \int_{t_0}^t |du(\tau_i)|}\right) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau}_{\text{Mechano-sorptive strain recoverable}} + \underbrace{\int_{t_0}^t m_{ms} \sigma(\tau) |U(\tau)| d\tau}_{\text{Mechano-sorptive strain irrecoverable}} \\ & - \underbrace{\int_{t_0}^t b \epsilon(\tau) du(\tau)}_{\text{Shrinkage/swelling strain}} + \underbrace{\int_{t_0}^t \alpha_u du(\tau)}_{\text{Inelastic strain}} \quad (8) \end{aligned}$$

where  $\epsilon$ ,  $J$ ,  $\sigma$ ,  $u$ ,  $t_0$ ,  $t$  and  $\tau$  are respectively the total strain, creep compliance, total stress, moisture content, initial time, final time and current time of the analysis. The term  $U$  refers to moisture levels not reached during the previous stress history. The model parameters that depend on material properties are  $c$ ,  $J_0$ ,  $m_{ms}$  and  $\alpha_u$ . The creep function  $J(t, \tau, u)$  is defined according to Toratti (1992) as:

$$J(t, \tau, u) = J_0(u) + J_c(t, \tau) = \frac{1}{E_0(1 - k_u u)} + \frac{1}{E_0(1 - k_u u_{ref})} \left( \frac{t - \tau}{t_d} \right)^m \quad (9)$$

where  $E_0$  is the elastic modulus of dried timber,  $u_{ref}$  is the reference moisture content,  $k_u$  is a model parameter, and  $t_d$  and  $m$  are material properties. The constitutive law represented by Equation 8 is the sum of the following terms:

**Elastic Strain:** The elastic strain depends on both the variation of stress (left component of the integral) and the variation of elastic compliance (right side of the integral) due to the change of moisture content, as reported in Equation 10:

$$\epsilon(t) = \int_{t_0}^t J_0(u(\tau)) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau + \int_{t_0}^t \sigma(\tau) \frac{\partial J_0(u(\tau))}{\partial u(\tau)} du(\tau) \quad (10)$$

**Creep Strain:** The creep strain developed in a single Kelvin chain  $n$  is described by Equation 11:

$$\epsilon(t)_{cr} = J_0(u_{ref}) J_n \int_{t_0}^t \left(1 - e^{-(t-\tau)/\tau_n}\right) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau \quad (11)$$

The total creep is the sum of the each Kelvin chain. The Kelvin chain is normally implemented within a numerical model, and it is particularly useful in case the stress acting on timber varies over time.



**Mechano-sorptive strain:** Mechano-sorptive strain is characterized by two contributions (Svensson and Toratti 2002): a recoverable part (left integral), and an irrecoverable (right integral) part according to Equation 12:

$$\epsilon(t)_{ms} = J^\infty \int_{t_0}^t \left(1 - e^{-c \int_{t_0}^{\tau} |du(\tau)|}\right) \frac{\partial \sigma(\tau)}{\partial \tau} d\tau + \int_{t_0}^t m_{ms} \sigma(\tau) |U(\tau)| d\tau \quad (12)$$

It can be seen that mechano-sorptive strain depends on both the stress  $\sigma$  and moisture content accumulation  $u$ . Regarding the left side of the equation, it is worthy to notice that the moisture term  $u$  compare in absolute value. This means that the process of mechano-sorptive depends on the accumulation of moisture cycles within the element that increases the rate of creep.

**Inelastic strain:** The inelastic strain due to moisture content changes is expressed by Equation 13:

$$\epsilon(t)_{im} = \int_{t_0}^t \alpha_u du(\tau) \quad (13)$$

with  $\alpha_u$  the moisture expansion coefficient.

**Shrinkage/swelling strain:** The shrinkage/swelling strain is expressed by:

$$\epsilon(t)_{ss} = - \int_{t_0}^t b \epsilon \tau du \tau \quad (14)$$

Equation 14 means that there is a sort of hysteresis in the behaviour. It can be noticed in fact that the /swelling contribution depends on the total deformation value.

## RHEOLOGICAL MODELS FOR TIMBER: ANALYTICAL APPROACH

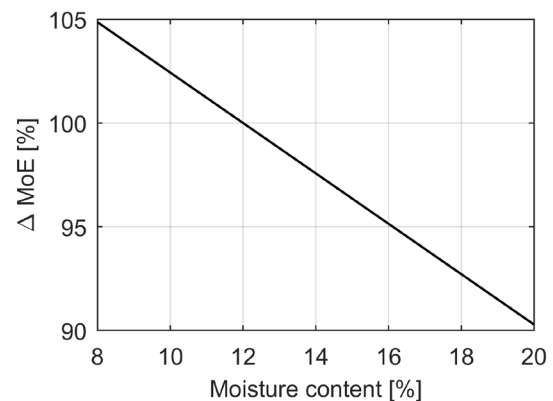
The constitutive represented by equation 8 has to be integrated by numerical methods to be solved, especially if the stress  $\sigma$  is varying over time. If the stress is constant, as currently assumed in the design practice by using the permanent load combination (section Standrads approach), Toratti's model can be presented in analytical form (Fragiacomo and Davies 2011). Written in this form, the model can be easily used for design purposes when looking at the building behaviour over time (Granello et al. 2018), and the designer can appreciate the influence of each component rather than just a unique creep coefficient. With regard to equation 8, each term is below expressed in analytical form and further discussed.

**Elastic strain:** The change of moisture content affects the elastic modulus (Equation 9), generating a self-

balanced stress. By considering known the elastic modulus  $E$  in correspondence of a moisture content  $u = 12\%$  as example, it can be written:

$$\frac{E(u)}{E(12\%)} = \frac{1 - k_u \cdot u}{1 - k_u \cdot 0.12} \quad (15)$$

If Figure 8, the variation of  $E$  is reported for different values of moisture content according to equation 9, normalized to the elastic modulus in correspondence of a moisture content equal to 12%. In his work, Toratti (1992) proposed a value  $k_u$  equal to 1,06. Considering the variability of the elastic modulus within the material itself, a variation of  $\pm 10\%$  due to variation of moisture content is not considered a particular issue from the self-balancing stress point of view.



**Figure 8:** Variation of modulus of elasticity with respect to moisture content according to Toratti (1992).

**Creep strain:** By assuming the stress constant and the problem linear viscoelastic, the creep deformation can be calculated as multiple of the elastic deformation. The pure creep coefficient  $\Phi_{cr}$  can be calculated by performing a creep test in constant environmental conditions. Often results are fitted by using a power law  $at^b$ , where  $t$  is time and  $a, b$  fitting parameters. Therefore, the creep coefficient  $\Phi_{cr}$  can be expressed as:

$$\Phi_{cr} = a \cdot t^b \quad (16)$$

As example, the pure creep properties of LVL Radiata pine are reported in Figure 9. These values were calculated by Davies and Fragiaco 2011, who tested several LVL block specimens 45 x 45 x 45 mm under compression force. The observations period was around a year, therefore, although the numbers obtained seems reasonable compared to the Standards (see section "Comparison between the methods"), there is some uncertainty in the extrapolation over 50 years. It has to be said however, that generally speaking creep tests are difficult to be monitored for more than 5-10 years (Ranta-Maunus and Kortessmä 2000), due to feasibility reasons.

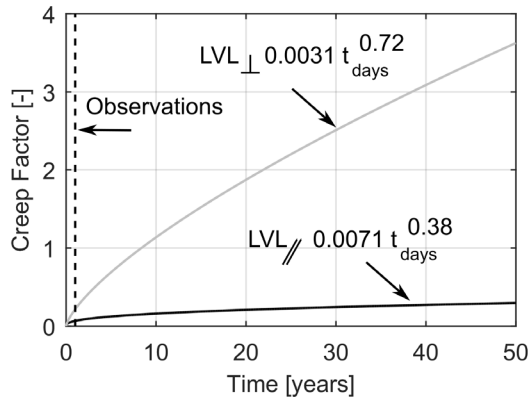


Figure 9: Pure creep properties of Radiata Pine LVL according to Davies and Fragiaco (2011).

**Mechano-sorptive:** In case of constant stress, the analytical expression of the mechano-sorptive component of the creep strain  $\Phi_{ms}$  can be re-arranged into to equation 17 (Fragiacomo and Davies 2011):

$$\phi_{ms} = \underbrace{\phi_{\infty} [1 - e^{-c U_{y,acc} t / (\Delta t)}]}_{\text{recoverable}} + \underbrace{m_{ms} (\Delta \hat{U})}_{\text{irrecoverable}} \quad (17)$$

where  $\Phi_{\infty}$ ,  $c$  material parameters,  $U_{y,acc}$  the yearly moisture accumulation and  $t$  time. It is worthy to notice that, on the contrary of pure creep which is increasing with time passing (equation 16), the recoverable mechano-sorption tends to a limit, which is  $\Phi_{\infty}$ .

In case of Radiata Pine LVL, the parameter  $\Phi_{\infty}$  was found equal to 0.63 and 0.5 respectively parallel and perpendicular to the grain (Fragiacomo and Davies 2011). Also regarding Radiata Pine LVL, the parameter  $c$  was found equal to 6.3 and 1 respectively parallel and perpendicular to the grain (Fragiacomo and Davies 2011).

From a design point of view, the problem to calculate  $U_{y,acc}$  can be simplified by assuming that timber element is subjected to the same humidity and temperature cycles each year. Eurocode 5, provides

(section "Standards approach") qualitative definitions of these environmental conditions. These qualitative definitions were expressed by analytical sine functions and reported in Figure 10.

The moisture transfer equation 6 was numerically solved (considering the diffusivity properties of LVL Radiata Pine) for the humidity conditions expressed by Figure 10 considering a timber beam protected at the extremities (i.e. humidity is not transferred parallel to the grain) with different sections. The expectation was in fact that big sections are less sensitive to humidity variations than small sections. This "size effect" is represented by the "wet perimeter" (WP) of a member, which is the area of the structural member divided by the perimeter exposed to the air where the moisture transfer occurs. Further details on the numerical integration can be found in Granello (2018). Results were fitted with an exponential functions and presented in Figure 11.

It can be noticed (Figure 11) that a section 400 x 240 mm (corresponding to a WP equal to 75 mm) presents an yearly moisture accumulation of circa 0.02 if subjected to the environmental conditions characterizing Service Class II. On the other hand, a greater section 500 x 500 mm presents an yearly moisture content of circa 0.015 when subjected to the same environmental conditions. This occurs because it takes time for the humidity to penetrate within the timber member, and therefore a more solid section is less sensitive to humidity variations. For Service Class III, with the assumption of complete saturation cycles provided by Eurocode 5 (i.e., moisture content variation between 8% and 30%) every year, the results are independent from the wet perimeter. The yearly accumulation of moisture content  $U_{y,acc}$  can be easily obtained by  $U_{y,acc} = 2 \cdot (U_{y,max} - U_{y,min}) = 0,44$ .

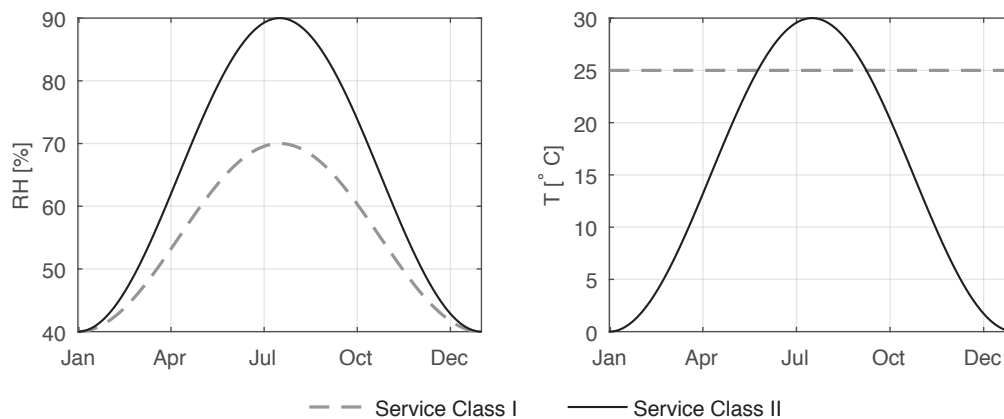


Figure 10: Graphical representation of the environmental conditions corresponding to Service Class I and II.

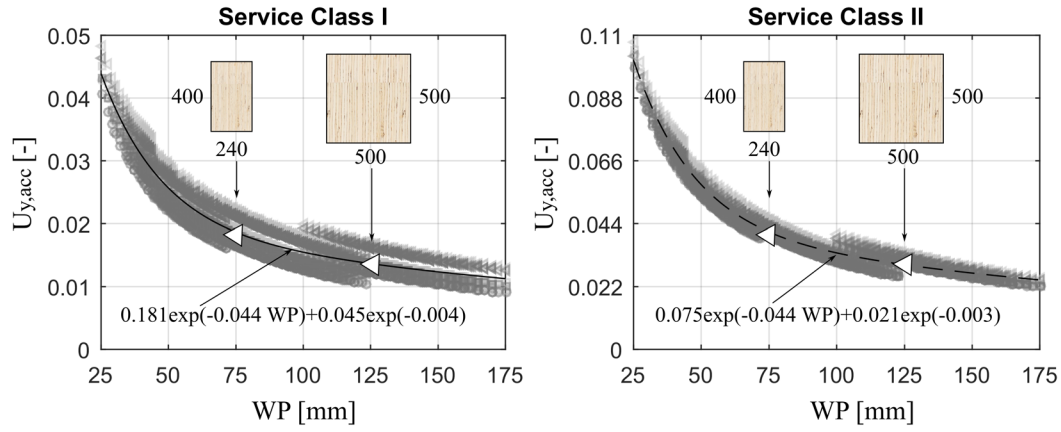


Figure 11: Yearly moisture accumulation  $U_{y,acc}$  for Service Class I and II.

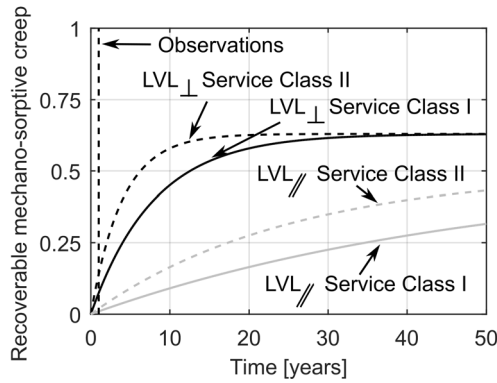


Figure 12: Mechano-sorptive creep parameter for a Radiata Pine LVL member with section 400 x 240 mm in Service Class I and II.

As example, in Figure 12, the recoverable mechano-sorptive creep is presented for a timber member with section 400 x 240 mm with respect to Service Class I and Service Class II, in case of load parallel to the grain.

Regarding the irrecoverable part of mechano-sorptive, it depends on the term  $\Delta\hat{U} = |\hat{U} - U_0|$ , where  $\hat{U}$  is defined as the maximum value of moisture content reached during the life of the structure. The values of

$\hat{U}$  are reported in Figure 13 for LVL Radiata Pine with respect to the wet perimeter and the Service Class. They depend also on the initial moisture content  $U_0$  of timber. Further details can be found in (Granello 2018).

It can be noticed that if timber has an initial moisture content  $U_0$  below 12%, it will probably experience a higher moisture content during its life, especially if subjected to Service Class II conditions. The value of the model parameter  $m_{ms}$  was proposed equal to 3.3MPa<sup>-1</sup> by (Svensson and Toratti 2002) for spruce timber perpendicular to the grain, but, in case of Radiata Pine LVL, the model parameter  $m_{ms}$  was found equal to 0 (Fragiacomo and Davies 2011) (which means that the irrecoverable part of mechano-sorptive is negligible for this specific engineered wood product).

Inelastic strain The inelastic strain of timber can be calculated by using to Eq. 18:

$$\epsilon_{in} = \alpha_u [U_{sv} - U_0] \quad (18)$$

where  $U_{sv}$  represent the average moisture content of timber in service, and  $\alpha_u$  a material parameter. Based

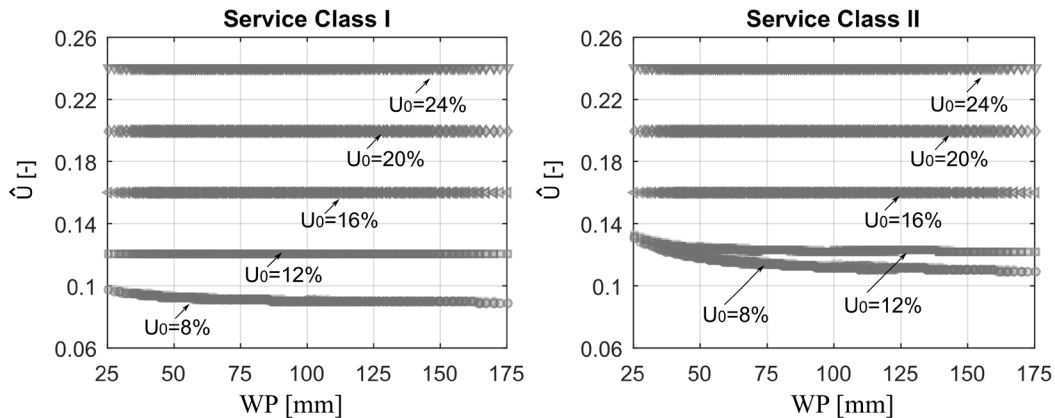


Figure 13: Maximum moisture content  $\hat{U}$  reached by timber in different Service Classes based on initial moisture content  $U_0$ .

on the results obtained by (Davies and Fragiaco 2011),  $a_u$  is equal to 0.00625 and 0.00165 for Radiata Pine LVL loaded parallel and perpendicular to the grain, respectively. Depending on the Service Class and by using Rasmussen's formula (Rasmussen 1961),  $U_{sv}$  can be estimated equal to 10% and 12% for Service Class I and II, respectively.

### CREEP DEFORMATION OF A LVL BEAM: COMPARISON BETWEEN BUILDING CODES

The creep behaviour at 50 years of a simply supported Radiata Pine LVL beam (Figure 14) is calculated by applying the 4 procedures discussed above, i.e., New Zealand Standard 3603 (1993), Eurocode 5 (2004), National Design Specifications (2018) and the analytical model based on Toratti's (1992) constitutive law. The section of the beam is 360 x 180 mm (Figure 15), and Radiata Pine LVL properties are reported in Table 8. A permanent load  $q$  equal to 8 kN/m is assumed acting on the beam, and the initial moisture content of timber  $U_0$  is assumed equal to 12%. Three environmental conditions were considered, correspondent to Service Class I, II and III.

The maximum stress  $\sigma_{max}$  can be calculated according to equation 19:

$$\sigma_{max} = \frac{M_{max}}{I} \cdot \frac{h}{2} = \frac{qL^2h}{16I} = 6.4 \text{ MPa} \quad (19)$$

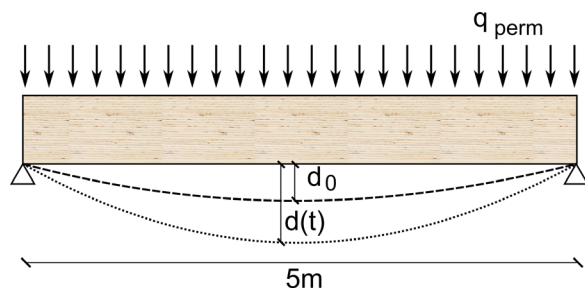


Figure 14: Radiata Pine LVL beam subjected to distributed load.

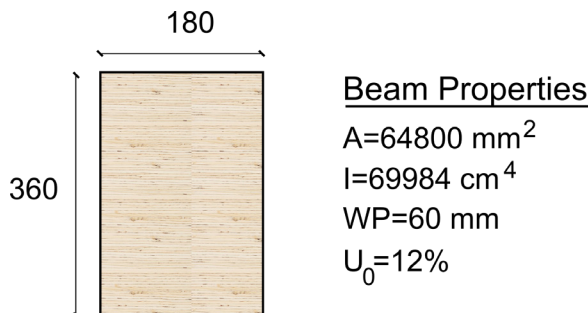


Figure 15: Beam's section properties.

Table 8: Radiata Pine LVL properties:  $f_b$  bending strength,  $f_c$  compression strength parallel to the grain,  $f_t$  tension strength parallel to the grain,  $f_s$  shear strength,  $f_p$  compression strength perpendicular to the grain,  $E$  elastic modulus and  $G$  shear modulus.

$f_b$	$f_c$	$f_t$	$f_s$	$f_p$	$E$	$G$
[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
48	45	30	6	12	11	550

It can be noticed that:

$$\frac{\sigma_{max}}{f_b} = 0.13$$

which is lower than the force reduction factors proposed by Eurocode 5, NDS and New Zealand Standard 3603, i.e., creep tertiary phase should be prevented. The elastic deflection of the beam  $d_0$  can be calculated by using the well-known Equation 20:

$$d_0 = \frac{5}{384} \cdot \frac{qL^4}{EI} + \frac{qL^2}{8GA_s} = 9.3 \text{ mm} \quad (20)$$

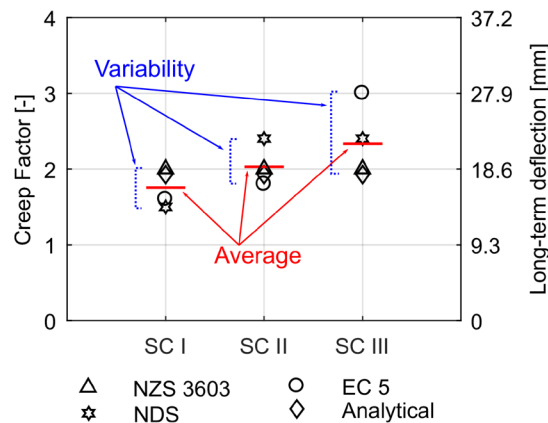
According to the New Zealand Standard, the deflection at 50 years  $d_{50}$  is equal to  $d_{50} = k_2 \cdot d_0 = 18.6 \text{ mm}$ . Note that this value is independent on the environmental conditions.

According to the Eurocode 5, the effective modulus of elasticity  $E_{eff}$  and shear modulus  $G_{eff}$  are affected by a coefficient  $k_{def}$  equal to 0.6, 0.8, 2 for Service Class I, II and III, respectively. Therefore, the deflection  $d_{50}$  is equal to 14.9 mm, 16.7 mm and 27.9 mm for Service Class I, II and III, respectively.

According to the NDS, the deflection at 50 years  $d_{50}$  is obtained by multiplying the elastic deflection  $d_0$  by the  $K_{cr}$  coefficient. Furthermore, in case of wet conditions the Elastic modulus  $E$  should be reduced by the appropriate  $C_M$  coefficient. Since LVL is not specifically addressed by the NDS, the coefficients proposed for Glue Laminated Timber are used in this worked example. It has to be noticed that both Eurocode 5 and New Standard 3603 propose the same coefficients for both LVL and Glulam. The values of  $K_{cr}$  are equal to 1.5 for Service Class I (assumed equivalent to dry conditions) and equal to 2 for Service Class II and III (assumed equivalent to wet conditions). The values of  $C_M$  for Service Class II and III is equal to 0.83, while  $C_M=1$  for Service Class I. Therefore, the deflection  $d_{50}$  is equal to 13.9 mm, 22.4 mm and 22.4 mm for Service Class I, II and III, respectively.

According to the Toratti's model (1992) calibrated on the experimental results obtained by Davies and Fragiaco (2011) and Fragiaco and Davies (2011), the pure creep coefficient is equal to  $\Phi_{cr} = 0.0071 \cdot t^{0.38} = 0.30$ . The recoverable part of the mechano-sortive creep  $\varphi_{ms,rec}$  is equal to 0.63 for all

the Service Classes (infact they all tend to the limit  $\Phi^-$ ). The irrecoverable part of the mechano-sorptive creep  $\varphi_{ms,irr}$  is equal to 0, when assuming the values proposed by Fragiaco and Davies (2011), i.e.,  $m_{ms} = 0$ . The resulting creep coefficient is equal therefore to 1.93, leading to a deflection  $d_{50}$  equal to 17.9 mm for all Service Classes. Results are resumed in Figure 16 and Table 9.



**Figure 16:** Creep factors (intended as amplification factors of the elastic deflection) and long-term deflections calculated by using New Zealand Standard 3603, Eurocode 5, National Design Specifications and Toratti's model.

**Table 9:** Creep factors (intended as amplification factors of the elastic deflection) calculated by using New Zealand Standard 3603 (NZS 3603), Eurocode 5 (EC5), National Design Specifications (NDS) and Toratti's approach. The variability is calculated as the difference between maximum and minimum amplification factors.

Approach	Creep factor		
	SC I	SC II	SC III
NZS 3603	2	2	2
EC 5	1.6	1.8	3
NDS	1.5	2.41	2.41
Toratti	1.93	1.93	1.93
Average	1.84	1.91	2.31
Max	NZS 3603	NDS	EC 5
Min	NDS	EC 5	Toratti
Variability	0.5	0.61	1.07

By looking at the values in Table 9, it can be noticed that the variability between maximum and minimum amplification factor increases with the Service Class. Specifically, the variability observed between the different approaches increases from 0.5 to 1.07.

These discrepancies are due to the creep factor dependency of environmental conditions in service. Specifically, the NZS 3603 does not take into account explicitly the environmental conditions the material will be subjected to, and therefore the mechano-

sorptive component of the creep does not change across the different service classes. The analytical approach based on Toratti's model takes into account the mechano-sorptive contribution. However, because the coefficient  $m_{ms}$  was proposed equal to 0 for LVL Radiata Pine (Fragiacomo and Davies 2011), the irrecoverable mechano-sorptive component is not affecting the results. Because the irrecoverable component of mechano-sorptive is dependent on the maximum level of moisture content reached, it mostly affects the response in Service Class III. In other words, it is believed that the great discrepancy between the different approaches is the correct quantification of the mechano-sorptive creep, which is affected by greater uncertainty with more extreme environmental conditions.

Furthermore, none of the approaches was found to be generally more or less conservative in terms of maximum and minimum amplification factors. For example, Eurocode 5 is the most conservative when looking at Service Class III, but the least conservative when looking at Service Class II. Similarly, the NDS was found to be the least conservative when looking at Service Class I, but the most conservative for Service Class II.

## CONCLUSION

A literature review presenting the general properties of creep, along with the best known conceptual models was presented in the first part of this paper. References to more refined constitutive laws were also reported.

From the design perspective, it was highlighted the connection between the theory and the equations provided by current Building Codes, specifically looking at the New Zealand Standard 3603, Eurocode 5 and the National Design Specifications: all approaches essentially rely on providing strength reduction factors to avoid the tertiary phase of creep, and on providing creep factors for multiplying the elastic deformation. This last procedure implicitly implies a linear visco-elastic creep development. While comparing the Standards, the following observations are made:

1. Eurocode 5 (2004) provides long-term deformation factors for amplifying the elastic deformation based on the Service Class, load duration and initial moisture content of timber. The National Design Specifications (2018)



provide amplification factors dependent on the service moisture content of timber, as well as on the load duration. The New Zealand Timber Standard (1993) provides amplification factors based on the initial moisture content of timber, as well as on the load duration. Based on the experimental observations and on the actual constitutive laws present in literature, mechano-sorption creep depends on the environmental conditions and therefore the effect of these last should be taken into account into the design approach.

2. The New Zealand Timber Standard (1993) proposes long-term deformation factors for amplifying the elastic deformation, also based on the stress nature, that is, differentiating between compression, bending, shear and tension. Based on the experimental observations and on the actual constitutive laws present in literature, the type of stress affects the creep factor and therefore it should be taken into account in the design approach.
3. The National Design Specifications (2018) propose strength reduction factors specific for each stress nature, i.e., compression, bending, shear, tension. Because the long-term creep deformation depends on the nature of the stress as experimentally observed, it is believed appropriate to provide such differentiation also in the in strength reduction factors.

A more comprehensive approach to calculate the viscoelastic deflection based on a well known constitutive law, i.e., Toratti's model (1992), was also reported. Each component contributing to the final creep coefficient was isolated and discussed.

Finally, the long-term deflection of a simply supported LVL beam was calculated. The calculations were performed according to Toratti's model, Eurocode 5, New Zealand Standard 3603 and National Design Specifications. When comparing the results, the following considerations are proposed:

1. The variability of the results was found increasing with the Service Class type. The discrepancies were due to the uncertain estimation of mechano-sorption effect.
2. None of the approaches was found generally more or less conservative with regard to the LVL beam example. Because the majority of the

experimental results in terms of creep are based on a period of observation lower than 10 years, it is difficult to identify which approach leads to the most accurate prediction over the life of a structure.

Given the complexity of the phenomenon, further research is necessary to refine the analytical approaches in terms of long-term behaviour of timber before any change could be recommended to parameters in New Zealand Standards.

## NOTATION

The following symbols were used in the paper:

$a, b$  = pure creep material parameters;

$A$  = shear area;

$C_M$  = wet service factor according to NDS;

$C_D$  = load duration factor according to NDSr;

$D$  = diffusion parameter for computing moisture content variations;

$E$  = Young's modulus;

$E_0$  = Young's modulus of dried timber;

$E_{eff}$  = Effective Young's modulus according to EC 5;

$h$  = height of the section;

$I$  = modulus of inertia;

$J$  = creep function definition;

$K_{cr}$  = creep deformation factor according to NDS;

$k_1$  = strength reduction factor according to NZS 3603;

$k_2$  = creep deformation factor according to NZS 3603;

$k_{def}$  = creep deformation factor according to EC5;

$k_{mod}$  = strength reduction factor according to EC5;

$k_u$  = material parameter affecting the Young's modulus of timber;

$q$  = distributed load;

$R_d$  = load carrying capacity (design value) according to EC 5 and NZS 3603;

$R_d$  = load carrying capacity (characteristic value) according to EC 5 or NZS 3603;

$r_p$  = relaxation function for steel;

$T$  = temperature;

$t$  = time;  
 $u$  = moisture content function;  
 $u_{ref}$  = moisture content reference value;  
 $U$  = timber moisture content accumulation;  
 $U_0$  = timber initial moisture content (at the time of loading);  
 $U_{y,acc}$  = average yearly moisture accumulation;  
 $U_{sv}$  = average timber moisture content in service;  
 $\hat{U}$  = maximum moisture content reached by timber since the time of loading;  
 $u$  = timber moisture content;  
 $u_{RH,T}$  = equilibrium moisture content based on Rasmussen's formula;  
 $W_{s, s1, s2}$  = parameters used in Rasmussen's formula;  
 $WP$  = wet perimeter;  
 Greek symbols:  
 $\alpha_u$  = dilation coefficient due to moisture expansion;  
 $\Delta_T$  = long term deflection according to NDS;  
 $\Delta_{LT}$  = deflection due to permanent loads according to NDS;  
 $\Delta_{ST}$  = deflection due to short-term loads according to NDS;  
 $\epsilon_{\infty}$  = long-term deformation;  
 $\epsilon_{el}$  = elastic deformation;  
 $\gamma_M$  = material safety factor according to EC 5;  
 $\sigma$  = stress acting on the element;  
 $\sigma_{lim}$  = stress limit to avoid the creep tertiary phase;  
 $\Phi_{cr}$  = experimental pure creep function for timber;  
 $\Phi_{ms}$  = mechano-sorptive creep function for timber;  
 $\Phi_{ms,irr}$  = irrecoverable component of the mechano-sorptive creep function;  
 $v\Phi_{ms,rec}$  = recoverable component of mechano-sorptive creep function;  
 $\Phi_{\infty}, c, m_{ms}$  = mechano-sorptive material parameters

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